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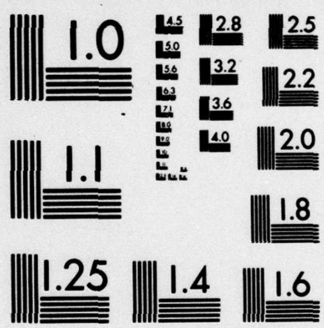


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# PROCESS MODEL OF HOW THE HUMAN OPERATOR TRACKS DISCONTINUOUS INPUTS


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Process Model of How The Human Operator Tracks Discontinuous Inputs

Richard J. Jagacinski, Walter W. Johnson,

E. James Hartzell, Sharon Ward, and Kaile Bishop

## Abstract

Two basic research projects were pursued. In conjunction with personnel at the 6570th Aerospace Medical Research Laboratory, Human Operator Effectiveness Branch, experiments determined that the time to acquire stationary targets with position and velocity control systems was a linear function of an Index of Difficulty measure. This measure, $\log_2 \left(\frac{2A}{W}\right)$, is a logarithmic function of initial target displacement, A, and target width, W. The linear relationship with capture time represents an extension of Fitts' Law, known to hold for discrete movements performed with a physical stylus. The slope of the linear relationship between capture time and the Index of Difficulty was considerably steeper for the velocity control system and was slightly steeper for greater initial target uncertainty.

The second project investigated the capture of moving targets with three different control systems: (1) two independent position controls, PP; (2) two independent velocity controls, VV; (3) one position and one velocity control, PV. The PV system yielded significantly faster capture times than the PP system. However, due to the development of two different control strategies with the VV system the difference between the VV and the other systems was not statistically significant. Further research is recommended to clarify this latter result.

# I. Capture of Stationary Targets

Richard J. Jagacinski, E. James Hartzell, Sharon Ward, and Kaile Bishop

Fitts' Law states that the time to complete a movement from a home position to a stationary target is linearly proportional to the logarithm of the required accuracy. This relationship has been found for movements of a physical stylus (Fitts and Peterson, 1964), but had not been previously tested for other system dynamics. Experiments were therefore conducted at the Human Operator Effectiveness Branch of the 6570th Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base to test whether this relationship would generalize to laboratory simulations of position and velocity control systems acquiring single dimensional stationary targets. This work has been recently published in The Journal of Motor Behavior and a copy of this paper is included in this report.

## II. Stimulus-Response Compatibility and the Capture of Moving Targets

Richard J. Jagacinski and Walter W. Johnson

Stimulus-response compatibility is a concept that has been introduced in reaction time research where it has been found that reaction times to a set of lights are faster and more accurate if the spatial arrangement of the lights corresponds in a simple manner to the spatial arrangement of the response buttons. In terms of a process model of human performance, one might postulate a stage of processing in which the stimulus information is mapped into an appropriate response. The simpler this mapping process, the more compatible the sets of stimuli and responses are said to be (Fitts & Seeger, 1953). In terms of discrete tracking, the dynamics of the plant being controlled strongly influence the form of the response, and this effect can be considered from the perspective of stimulus-response compatibility. For step inputs K, K/s, and $K/s^2$ plants respectively require step, pulse, and double-pulse responses for time optimal performance. These three responses can be considered successively more complex transformations from stimulus to response, and the data of McRuer et al. (1968) indicate that the time to complete such responses becomes correspondingly longer.

The corresponding data for constant velocity inputs apparently is not available. This task will be more complex than tracking a step input in that both the position and the non-zero velocity of the input must be matched by the human operator. The time optimal control patterns for K, K/s, and $K/s^2$ plants in this case are respectively a step-ramp sequence, a pulse-step sequence, and a double-pulse. The K/s system will likely be easiest to use to match the input velocity, but the additional constraint of matching the input position makes the response more complex.

One possibility for improving the performance of the human operator is to give him two controls in parallel for this task--independent K and K/s controllers, one controlled by each hand. The two degrees of freedom in the control mechanism would then correspond in a very direct, compatible manner to the two primary stimulus dimensions of the input, namely position and velocity. The required control movement is then simply a step-response with the K plant to match the input position, and a step response with the K/s plant to match the input velocity.

On the basis of stimulus-response compatibility, one would expect the response of this parallel K, K/s controller to permit faster capture than either a K or K/s system alone. Another reason to expect this system to permit superior performance is that it imitates the control structure of the human eye. Poulton (1974) has commented that the major difference between visual and manual tracking performance is the superiority of the eye in target acquisition. While there are probably a number of factors such as the torque to inertia ratio that contribute to this superiority, one likely factor is the separate responses made to the position and velocity of a visual target. Contemporary control models of the eye (e.g., Young et al., 1968) consist of a saccadic channel that responds to target position, and a parallel pursuit channel that responds to target velocity. The proposed manual controller configuration thus imitates this structure.

In present target acquisition systems, human operators typically have a choice of using K or K/s control, but are not permitted to use both in parallel. The K system is often used for acquisition and the K/s system thereafter. By having both systems in parallel, the human operator may be able to obtain faster acquisition and a smoother transition from acquisition to close following behavior. Improved tracking might also result at target crossover, where the typically observed increase in tracking error can be considered as reintroducing the acquisition problem.

In order to test these ideas, the acquisition of moving targets was investigated with three different control systems: 1) two independent position controls, PP; 2) two independent velocity controls, VV; and 3) one position and one velocity control, PV. Ideally a single position control and a single velocity control might also be included for comparison. However, as an initial step in this research, it was felt that the PP and VV systems with their extra degrees of freedom would provide a stronger test against the supposedly highly compatible PV system.

## Method

### Apparatus

The target acquisition system was simulated on an EAI Pace TR-48 analog computer. The target appeared as two 1.5 cm vertical lines moving horizontally across a 10 cm wide oscilloscope screen. A strip of yellow tape 1 mm wide by 20 mm long was positioned vertically at the center of the screen and served as the zero error reference marker. A chair was positioned such that the distance from the subjects' eyes to the screen was approximately 50 cm. At this distance the screen spanned $11.5^{\circ}$ of visual angle and the target horizontally spanned $0.1^{\circ}$ of visual angle.

Two control sticks were mounted 30.5 cm apart on the surface of a table which was 76 cm high. The subjects were free to position the table at a comfortable distance in front of them, but were not allowed to alter the position of the chair. The control sticks were pivot mounted and allowed approximately 30$^{\circ}$ of free excursion to the right or left.

During each experimental session the subjects wore headphones over which they heard either a 390 Hz tone, white noise, or the experimenter's voice. The tone was used to alert subjects to upcoming trials and to provide feedback.

The gains for the position and velocity systems were selected upon the basis of data collected in two pilot studies run prior to the experiment. In the first pilot study six subjects used a single right-hand velocity control and six subjects used a single right-hand position control. Two types of targets, which were among the set of targets used in the subsequent experiment, were presented to each subject at each of four levels of gain. The two targets were a slow, wide target initially moving toward center of the oscilloscope screen, and a fast, wide target initially moving away from the center of the screen (see the Design section for a more complete description of the target parameters). For the subjects using a velocity control, the four gains were .165 cm/s (.19$^{\circ}$ visual angle/s), .33 cm/s (.38$^{\circ}$ visual angle/s), .66 cm/s (.76$^{\circ}$ visual angle/s), and 1.32 cm/sec (1.52$^{\circ}$ of visual angle/s) per 1$^{\circ}$ deflection of the control stick. For the subjects using the position plant the four gains were .33 cm (.38$^{\circ}$ visual angle), .66 cm (.76$^{\circ}$ visual angle), 1.32 cm (1.52$^{\circ}$ visual angle), and 2.64 cm (3.04$^{\circ}$ visual angle) per 1$^{\circ}$ deflection of the control stick. Subjects received 40 trials on each of the four gains for three days. The order of presentation on any given day was from least to most sensitive for half the subjects, and from most to least sensitive for the remainder. The mean capture times were calculated for each subject for each gain on the second and third days of practice. On the basis of these results, a gain of .76$^{\circ}$ visual angle per 1$^{\circ}$ stick deflection was chosen for the position control, and a gain of .38$^{\circ}$ visual angle/s per 1$^{\circ}$ stick deflection was chosen for the velocity control.

In a second pilot experiment two subjects used the PP control system and two subjects used the PV control system for 5-7 days. The capture times were much higher than were obtained with similar subjects using a lower gain on the position control, and one of the PV subjects complained that the position control was so sensitive that he relied only on the velocity control. Therefore, a lower gain of .38$^{\circ}$ visual angle per 1$^{\circ}$ stick deflection was chosen for the position control for subsequent experimentation. This sensitivity was the lowest gain that would permit subjects to capture the moving targets with the position control alone if they chose to use it singly for 4S.

Subjects

Twenty-one Ohio State University students participated in eight one-half hour sessions each. Of these subjects 15 were male and six were female. For the first four days of the experiment the subjects either received credit for an optional assignment in an introductory psychology course or were paid $2.00 per session. For the last four days of the experiment all subjects received cash payments according to the formula:

$$Y = -.625X + 3.375$$

where Y represents the cash payment in dollars, and X represents the mean capture time in seconds for that session. The only exception to the above formula was that no subject could receive less than $1.75 for any session.

Design

Subjects were randomly assigned to one of three control system configurations. In one configuration the subjects controlled independent position plants with both their right and left hand (PP); in a second configuration the subjects controlled independent velocity plants with their right and left hands (VV), in a third configuration the subjects controlled a position plant with one hand, and a velocity plant with the other hand (PV). For all three configurations, the outputs of the two independent plants were summated to determine target position. Early in running it was discovered that there were wide differences in performance based upon the sex of the subject, and therefore the data of the male and female subjects were treated. separately. More males than females were run since it was desired that subjects be close to their asymptotoic performance by Day 8, and it was assumed that the male subjects were, on the average, starting at a point closer to their asymptotic levels. Finally, for the PV control system, the two female and three of the male subjects utilized a left-hand position control and a right-hand velocity control. The other two male subjects utilized a left-handed velocity control and a right handed position control.

Three within-subject variables were manipulated: 1) target width, the gap between the two 1.5 cm lines, was either 2 or 4 mm; 2) the initial target velocity was either 11.5 or 23.0 mm/s, which corresponded to $1.32^{o}$ or $2.65^{o}$ visual angle/s; 3) the initial position/direction of the cursor was such that the target either appeared 4 mm from center and moving away from the center of the screen, or 50 mm from the center of the screen and moving toward the center.

Procedure

On the first day subjects received 8 blocks of 10 trials each to familiarize them with the control systems. The subjects alternated across blocks using the right hand control stick alone for a block of trials and then the left hand control stick alone for a block of trials. Within each ten-trial block the target appeared randomly to the left or right of center with the stipulation that there were five trials appearing to the left and five trials appearing to the right. Subjects received four blocks of trials with an initially stationary target and then four blocks of trials in which the initial target velocity equal to 11.5 mm/s. It was hoped that this first day procedure would allow the subjects to obtain an unambiguous perception of how each of their control sticks affected the displayed position of the target.

For the remaining seven days, the subjects were permitted to use either or both of the two control sticks on all trials. They received 160 trials per session divided into 16 ten-trial blocks. Total capture time was summed over each of these 10-trial blocks. Again, the target appeared randomly to the left or right of center within each of these blocks with the constraint that there be five of each type. These 16 blocks were divided into eight sets of two blocks each. In each of these sets the subjects received one of the eight possible combinations of target width, initial velocity, and initial position/direction. These sets were randomly ordered within sessions, but the subjects were informed prior to each set about which type of target would be appearing next.

The subjects were instructed to manipulate their control sticks so as to move the target to the center of the oscilloscope screen as quickly as possible, and to hold it over the reference line at the center of the screen for at least 400 msec. The subjects were further told that if they failed to capture the target within four seconds, the trial would be terminated. One second prior to each trial the warning tone was sounded over the subjects' earphones to alert him to the upcoming trial. If the subject failed to capture the target within the four second time limit, the tone was again sounded contiguous with the termination of the trial to signal that the subject had failed on that trial. The intertrial interval within each set of ten trials was five seconds. At the end of each session, a subject was told his mean capture time for that day.

## Results

### Male Subjects

The average capture time minus the 400 msec capture criterion for the five male subjects using each type of control configuration is displayed over days in Figure 1. Although none of the three groups changed by more than 5% from Day 7 to Day 8, a performance asymptote seems most firmly established for the VV control group. When just the last two days performance are considered, a wide range of inter-group variability was observed. The error variances for the three conditions are .004 $sec^2$ for the PP condition, .018 $sec^2$ for the PV condition, and .198 $sec^2$ for the VV condition. The relatively high variability in the VV condition is partially attributable to strategy differences among subjects. Two subjects in this group regularly banged the control sticks to their full limits at the beginning of a trial, and had markedly shorter capture times than the other three VV subjects (Figure 2). Due to this high variability within the VV group, a between group statistical comparison was only made between the PP and VP groups. A t-test revealed that on Days 7 and 8 the subjects utilizing the PV controls had significantly lower capture time ($p < .05$) than the subjects utilizing the PP controls.

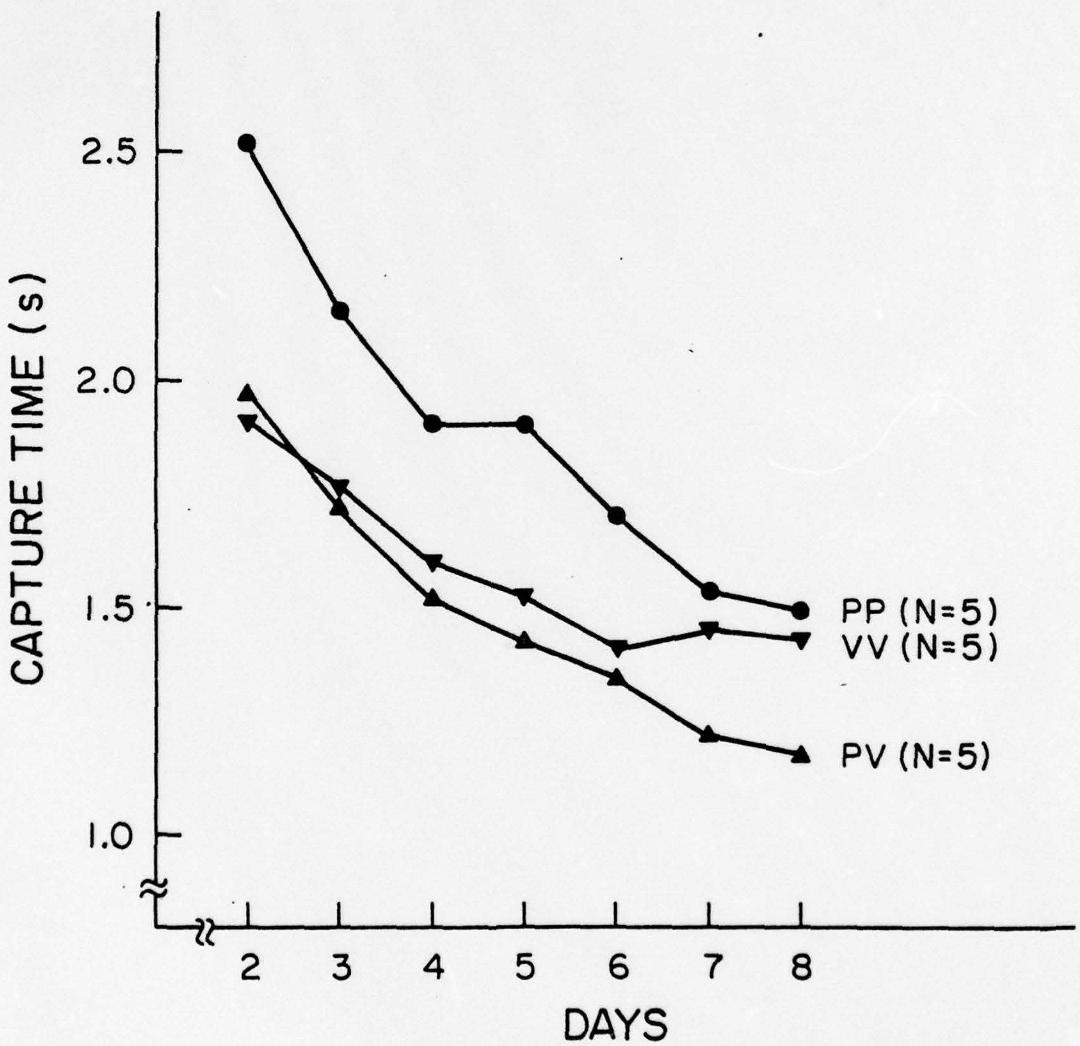


Figure 1 - Mean capture time for five male subjects for each of three different control systems.

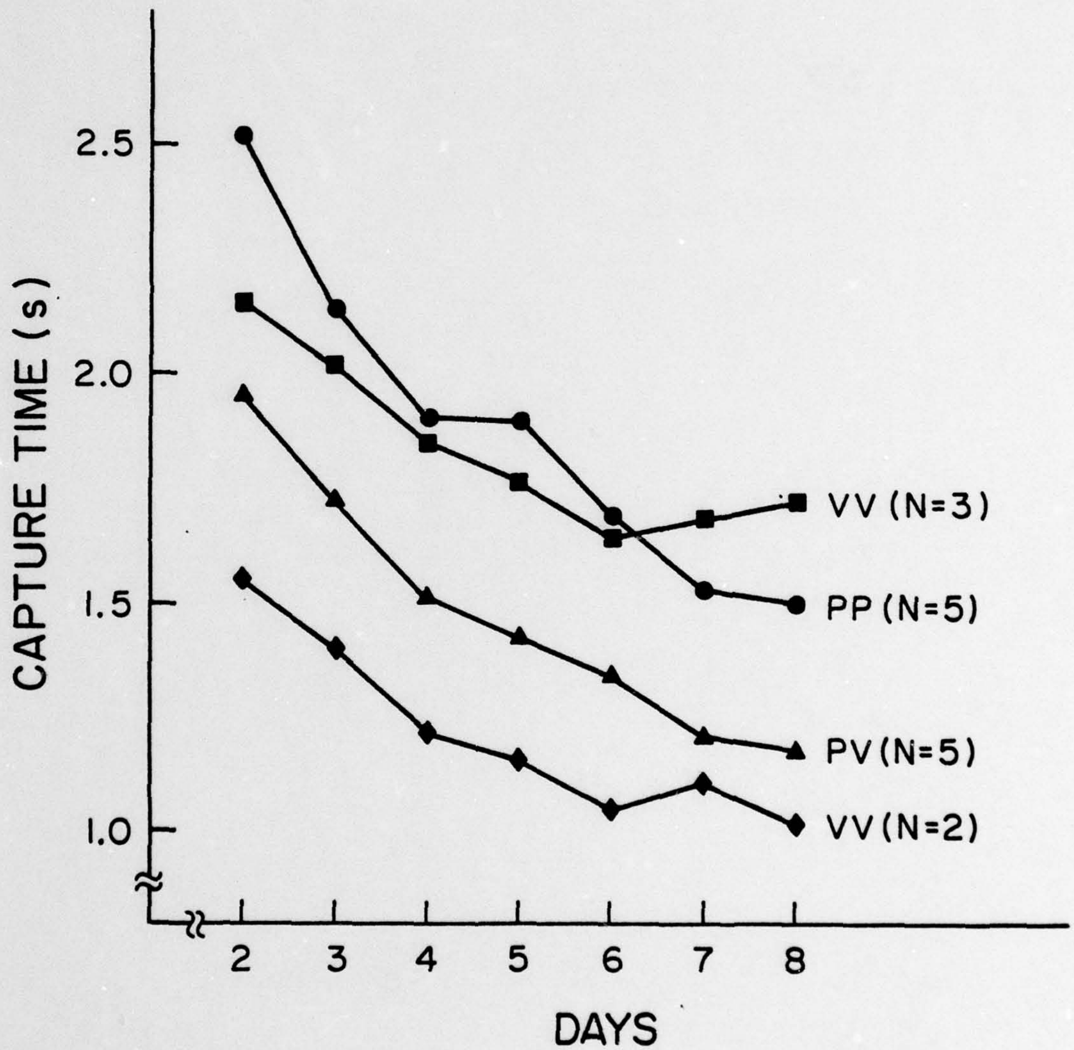


Figure 2 - Mean capture times for five male subjects for each of three different control systems. Subjects with the VV system have been split into two groups corresponding to three subjects who did not bang the control sticks to their full limits, and two subjects that did.

Due to the nature of the mixed experimental design used, all of the tests for the significance of the main effects of the within-subjects variables, and all tests for the significance of interactions could be conducted despite the different between-group variances. Due to the complexity of the comparisons however, it was decided to do four separate analyses of variance, one directly comparing all three control configurations, and then three analyses of variance comparing the three control configurations in pairwise fashion. In all four of the analyses the main effects of target width, initial velocity, and initial position/direction were all found to be significant ($p < .01$). These effects are graphed in Figure 3. Also, in all of the analyses the speed X control system interaction was found to be significant ($p < .05$), while in three of the four analyses the position/direction X speed interaction was found to be significant ($p < .05$)(it was absent in the PP-PV comparison).

Three other significant interactions were found in three of the four analyses. These interactions were a width X speed interaction, a control system X width interaction, and a control system X speed X width interaction. None of these interactions were present in the analysis comparing the VV with the PV group. Since the controller X speed X width interaction is the highest order interaction and modifies all of the others, it is displayed in Figure 3. This figure suggests that the interaction is caused by the relative breakdown of performance for fast-narrow targets in the PP group. There seems to be very little difference between the VV and the PV groups as would be expected by the absence of the interactions in the comparison of these two conditions.

In sum, the results of the analysis of the data for the male subjects suggests that the performance of subjects utilizing the PP control configuration is qualitatively different from the performance of subjects utilizing the VV or the PV control configurations, and that these latter two conditions

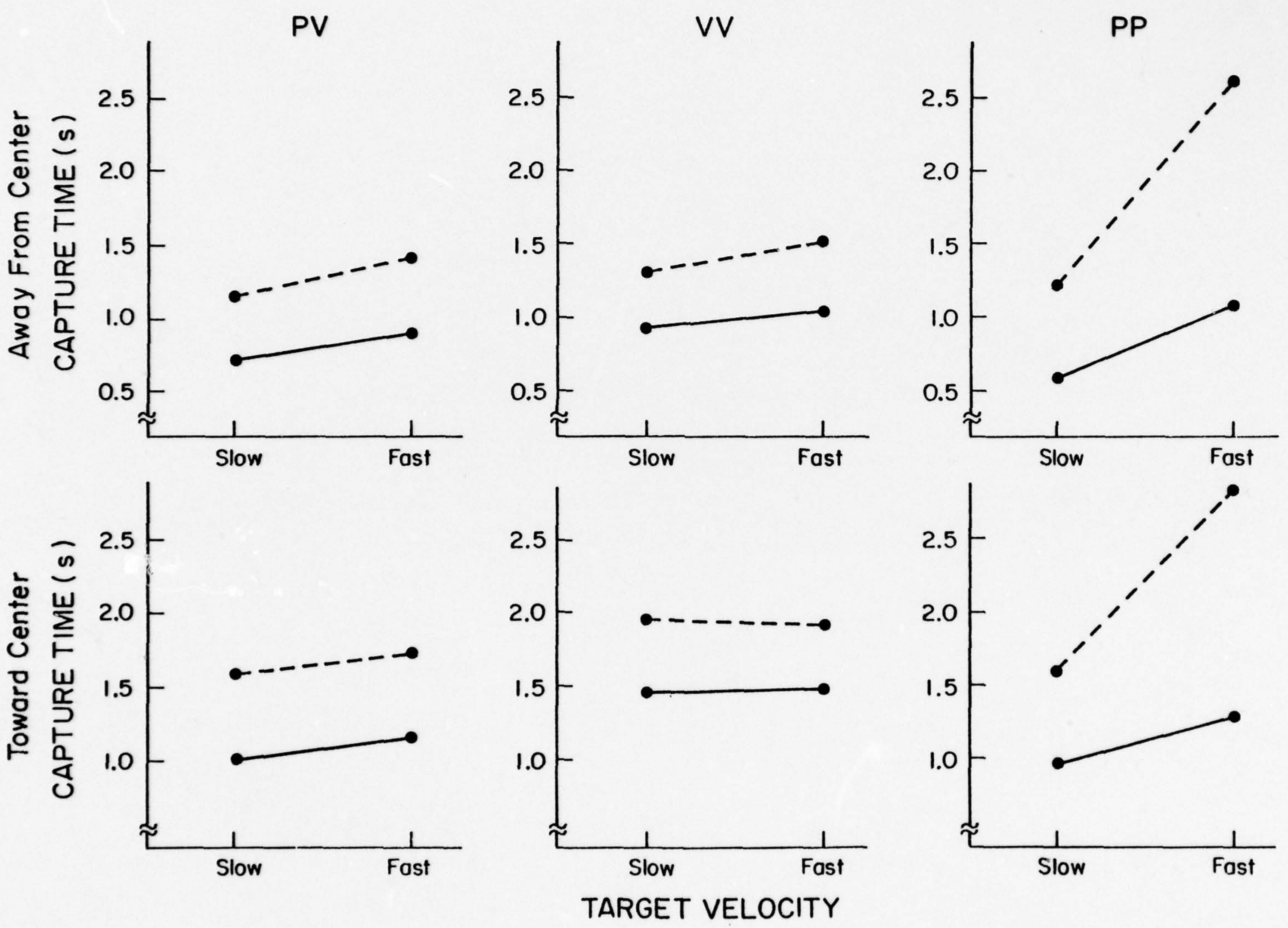


Figure 3 - Mean capture times for each type of target for five male subjects for each of three control systems. Dashed lines represent narrow targets; solid lines represent wide targets.

differ very little in the way they utilize their controls as far as terms of the pattern of capture times.

Female Subjects

The data for the female subjects shown in Figure 4 roughly paralleled the trends exhibited by the male subjects. The ordering of control configurations in terms of average capture time again showed the PP configuration to be worst and the PV condition best. Due to the small number of female subjects however, detailed statistical analyses were not performed.

## Discussion

Although the present experiment did not establish whether the VV or PV system will result in faster target acquisitions, the PV system was significantly better than the PP system. This latter system showed an extremely large increase in capture time for the fast and narrow target, while affording relatively short capture times for the other targets. Apparently, the task of generating a fast ramp-like movement and additionally generating fine position corrections is very difficult for the human operator. The other two systems permit velocity matching with a step movement rather than a ramp-like movement.

In order to determine the relative superiority of the VV and PV systems, the gain of the velocity controls should be increased. Although the pretest showed little difference among the several values of gain, the pretest was based on relatively little practice. It would not be surprising that subjects prefer higher gains after sufficient practice permits them to make more sensitive control adjustments. The tendency for two of the subjects using the PV system to bang the control stick to its extreme positions late in practice is consistent with this hypothesis. It should be noted that in the

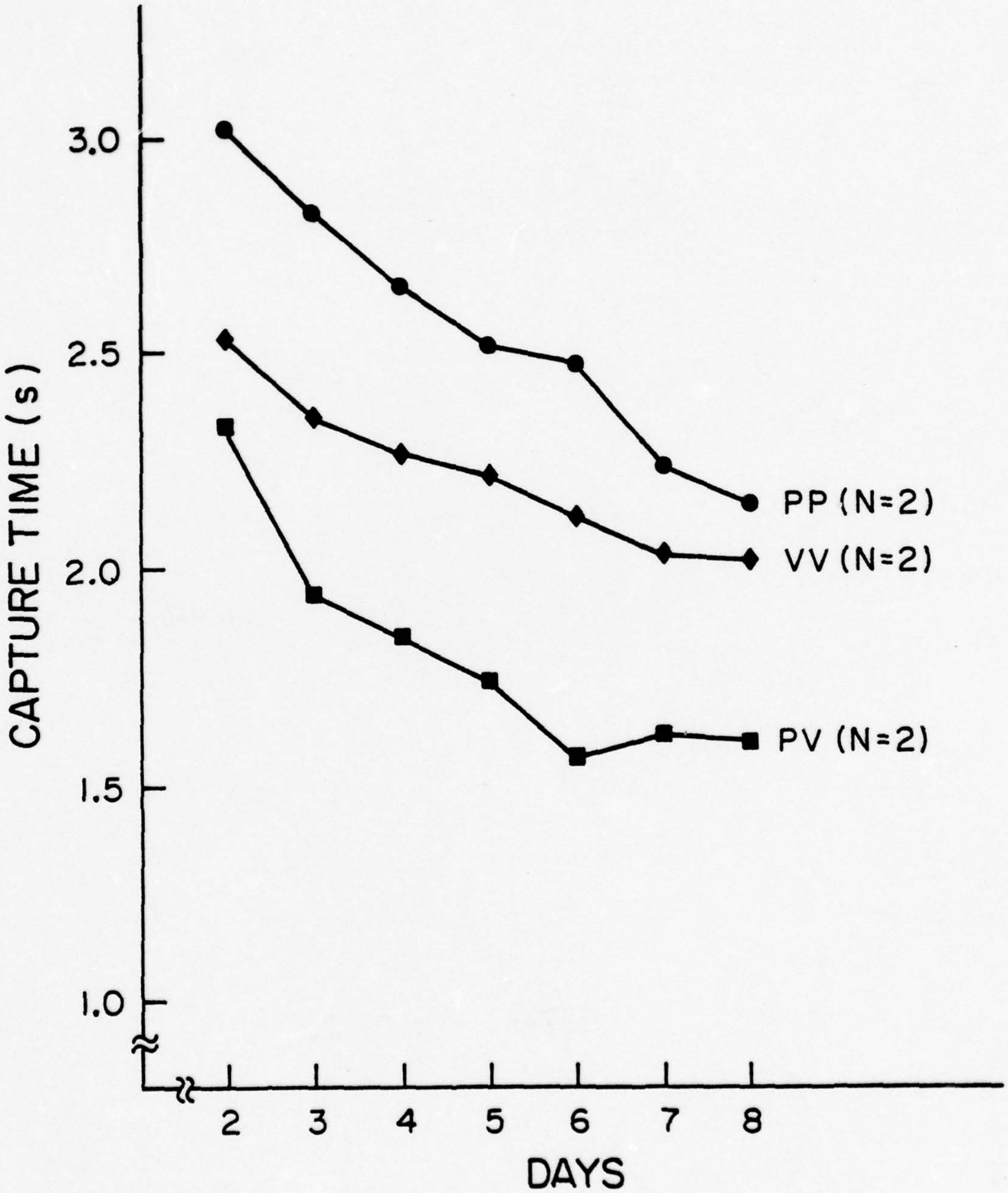


Figure 4 - Mean capture times for two female subjects
for each of three different control systems.

present experiments the values of all the velocity controls were identical. It might be that the ideal gain for the velocity control in the PV system is not the same as that for the VV system, or than two different gains might prove more beneficial for the VV system. These possibilities are beyond the scope of the present research effort.

The present experiments so far have only used capture time as a summary performance measure with which to assess the attribute of stimulus-response compatibility for the several control systems being tested. The system permitting faster captures is said to have greater compatibility. Although this approach has generally been used in experimental psychology, it is far from being totally satisfactory. Many processes may intervene between the presentation of a stimulus and the execution of the response, and the limited structure of unidimensional reaction time or capture time measures makes the task of inferring these underlying processes all the more difficult. For example, in the present experiments it might not be the mapping from stimulus dimensions to response dimensions that makes the PP system harder to use. The task of executing an accurate ramp-like movement may in itself simply be a more difficult maneuver than executing an accurate step-movement. In this case, it would be the form of the response elements, rather than the mapping of these elements onto stimulus dimensions that leads to poorer performance. Fortunately, in the area of motor behavior there is a great deal of structure in the patterns of the observable movements. It is this structure that must be utilized to more carefully delineate the concept of stimulus-response compatibility. One promising mathematical technique for capturing this structure is the discrete control methodology recently developed by R. A. Miller (1977). Utilizing this approach for target acquisition behavior will involve defining two sets of primitives corresponding to a basic set of response elements and a basic set of stimulus categories. The response elements might be simple maneuvers like pulses, steps, and ramps; the stimulus categories will describe the relative convergence of the target toward the desired reference point. The discrete control methodology will then describe a finite state transition pattern among the response maneuvers, conditional on the convergence pattern of the target. The resulting transition matrices will provide a summary of the probabilistic mapping of stimulus patterns to response maneuvers, which is the very issue addressed by the concept of stimulus-response compatibility. This methodology will hopefully push a step closer to the goal providing a more process oriented model of the capture behavior of the human operator.

Fitts, P.M. & Seeger, C.M. SR compatibility: Spatial characteristics of stimulus and response codes. Journal of Experimental Psychology, 1953, 46, 199-210.

McRuer, D. T., Hoffman, L. G., Jex, H. R., Moore, G. P., Phatak, A. V., Weir, D. H., & Wolkovitch, J. New approaches to human-pilot/vehicle dynamic analysis. Wright-Patterson Air Force Base, Ohio, AFFDL-TR-67-150, February, 1968.

Miller, R. A. Identification of finite state models of human operators. Modelling and Simulation, 1977, 8, 923-926.

Poulton, E. C. Tracking skill and manual control. New York: Academic Press, 1974.

Young, L. R., Forster, J. D., & Van Houtte, N. A revised stochastic sampled data model for eye tracking movements. Proceedings of the Fourth Annual NASA-University Conference on Manual Control, 1968, 489-508.

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**FITTS' LAW AS A FUNCTION OF SYSTEM DYNAMICS AND TARGET UNCERTAINTY**

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*Fitts' law was found to hold for discrete movements executed by subjects controlling the velocity of a cursor with a control stick. The slope of movement time versus index of difficulty was approximately twice as large as for a comparable position control system. Target uncertainty also increased the slope of total time versus index of difficulty, and this effect is interpreted in terms of adaptive tuning of the human movement system.*

In the study of discrete movements, it has been demonstrated that more accurate movements take longer to execute. For example, if a person is asked to move the tip of a stylus as quickly as possible from some home position to a target area to the right or left, movement time (i.e., the interval from the initiation of movement until the stylus reaches the target) is proportional to $\log_2(2A/W)$, which is referred to as the index of difficulty (Fitts & Peterson, 1964). $A$ is the distance from the home position to the center of the target, and $W$ is the width of the target. The quantity $A/W$ can be considered a measure of proportional accuracy of the

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required movement, and the linear relationship between $\log_2(2A/W)$ and movement time is commonly referred to as Fitts' law.

A primary concern of the present experiment was the effect of system dynamics on Fitts' law. If a person is required to move a stylus from a home position to a target, the required movement pattern of the person's hand and the motion of the stylus follow each other in a one-for-one relationship. This relationship can be made more indirect by allowing a subject to manipulate a control stick that will move the displayed image of a cursor from a home position to a target. The relationship between control stick movement and cursor movement can then be varied. For example, Sheridan and Ferrell (1963) and Ferrell (1965) studied the time to complete discrete grasping maneuvers with a remote manipulator when time delays of 1-3 sec were introduced between movement of the master control and the response of the slaved manipulator. They reported a linear relationship between the logarithm of the time to complete the maneuver and an index of difficulty measure. McGovern (Note 1) also investigated movements performed with remote manipulators and found a linear relationship between the time to complete a peg-transfer task and index of difficulty.

The present experiment compared subjects' ability to perform discrete movements when control-stick manipulation controlled the position or the velocity of a cursor. The time optimal pattern for making a discrete change in cursor position with a position control system is simply a step-like change in control stick position (Figure 1). In contrast, the time-optimal pattern for making a discrete change in position with a velocity control system is a pulse whose amplitude is as large as the system will permit, and whose duration is just sufficient to bring the cursor to the center of the target (Figure 1). The cursor thus travels with the maximum constant velocity allowed by the system from some initial position to the target. The trailing edge of the pulse sets the cursor velocity back to zero upon reaching the target.

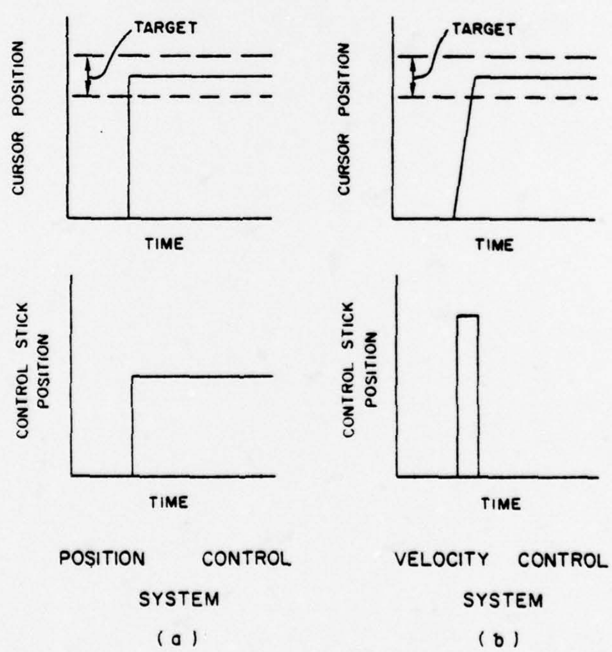


Fig. 1. Time optimal manipulation of a control stick to bring the cursor to the center of the target region with (*a*) a position control and (*b*) a velocity control system.

One might argue that a pulse response represents a more complex movement pattern than is required by a position control system, because the pulse essentially consists of two consecutive step changes of equal magnitude and opposite direction. In the present experiment, the velocity system was sufficiently sensitive so that subjects did not use the maximum possible system velocity, and the leading edge of the pulse was therefore not simply a movement to a fixed stop. From another point of view, the velocity control system can be thought of as providing less direct, less "compatible" control of cursor position. From either point of view, one would expect both reaction times and movement times to be longer than with a position control system (e.g., see Gibbs, 1963; McRuer, Hofmann, Jex, Moore, Phatak, Weir, & Wolkovitch, 1968). Along this line of reasoning, one explanation of Fitts' law for position control systems posits a sequence of submovements of equal duration (Crossman & Goodeve, Note 2; Keele, 1968). Since submovements with the velocity control system would be expected to be of longer duration due to greater complexity or incompatibility, one would expect the slope of the possibly linear relationship between movement time and the index of difficulty to be steeper with the velocity control system. The present experiment tested whether the relationship between movement time and index of difficulty was linear for the velocity control system.

In contrast to the strong relationship between movement time and the index of difficulty found in previous research, reaction time (i.e., the interval from the experimenter's signal to move until the subject initiates a movement) is much less affected by the relative accuracy of the movement (Fitts & Peterson, 1964). Reaction time tends to be more strongly affected by uncertainty as to which movement will be required (Ells, 1973; Fitts & Peterson, 1964). Although uncertainty also has some effect on movement time, these effects tend to be considerably smaller than the effects of the required accuracy. A number of authors have interpreted these results as indicating that reaction time and movement time reflect relatively independent processes (e.g., Fitts & Peterson, 1964). Previous manipulations of uncertainty, however, have only involved whether or not a predetermined movement is to be executed, and which of two targets a subject is to reach. The present experiment manipulated the number of possible targets more extensively by comparing movement times and reaction times when the subject could expect one of two possible targets differing only in direction, and when he could expect one of 24 possible targets differing in direction, amplitude, and width. This manipulation provides an additional test of whether the predominant influence of uncertainty is on reaction time rather than movement time.

## Method

*Apparatus.* A joystick was mounted at the end of an armrest that was elevated 10° from horizontal. The joystick was inclined 6° from vertical toward the subjects and required 70 gm of force to overcome a spring restraint. Full excursion of the joystick was approximately ±30° to the right or left.

The position and velocity control systems were simulated on an Electronic Associates Pacer 600 Hybrid Computer. The cursor and target were displayed on a 38-cm x 28-cm Hewlett Packard 1310A Display with P24 phosphor. Control system output was sampled once every 5 msec and stored on magnetic tape.

*Subjects.* Subjects were five male and three female members of a paid subject pool, who ranged in age from 18 to 24 yr. Subjects were ranked according to time-on-target scores in previous studies involving capture of a moving target with position and velocity control systems and subsequent continuous tracking with a velocity control system. Based on these rankings, subjects were split into two groups each containing four subjects. The subjects' rankings closely corresponded to their degree of tracking experience, which ranged from 2 to 3 yr for the top four subjects, and from 3 months to 1 yr for the lower four subjects.

*Procedure.* Subjects sat in a darkened room and were positioned so that their eyes were approximately 1 m from the oscilloscope screen. They communicated with the experimenter through a microphone and headset. At the beginning of each experimental trial a cursor consisting of an 18-cm vertical line appeared in the center of the oscilloscope screen. Two sec later a target consisting of a pair of 9-cm vertical lines appeared randomly to the right or left. The subjects' task was to manipulate the joystick so as to bring the cursor between the two target lines as quickly as possible. In order to preserve a stimulus-response compatibility relationship consistent with subjects' previous tracking experience, the display was "inside-out," so that movement of the joystick to the right resulted in the target moving to the left and the cursor remaining in the center of the oscilloscope screen. The display thus simulated the effect that would be obtained by centering a "viewing window" over an external stationary target. When the cursor remained "relatively still" within the target for 350 msec, the trial was over and the cursor and target disappeared from the screen. "Relatively still" was defined as cursor movement being less than .417 mm over each of the seventy 5-msec periods comprising the 350-msec duration. Following the end of a successful trial, the screen remained blank for 3 sec and then the next trial began. If the subject failed to achieve the 350-msec criterion within 5 sec of the appearance of the target, the trial automatically ended. The target disappeared from the screen, but the cursor remained on for 2 sec to indicate to the subject that he had failed to meet the criterion. Subjects were instructed to try to get the target to the center of the screen and make the screen go blank as quickly as possible. At the end of each day's performance, subjects were told the mean time taken to make the screen go blank over all trials, and at the beginning of each experimental session they were shown a graph of their mean time over days to encourage rapid performance.

Reaction time was measured from the appearance of the target on the screen until the subject moved the joystick .6°, which was 2% of full deflection. Movement time was measured from the end of the reaction time interval until the subject began a 350-msec period of holding the target relatively still over the cursor. Both reaction time and movement time were measured to the nearest 5 msec.

Two types of control systems were used, a velocity control and a position control. Using the results of Gibbs (1963) as a guideline, several subjects not used in the primary experiment were pretested with various gain settings on each system. Gains of .418° and 3.0°/sec of visual angle per 1° of control stick displacement were chosen for the position and velocity systems, respectively. The velocity control system was sufficiently sensitive that subjects did not use the full limits of control stick excursion.

*Design.* For each of the two levels of subjects, half were randomly assigned to the velocity control system and half to the position control system. Each experimental session consisted of 216 trials, 1 practice trial and 8 data trials for each of 24 different targets. The targets were generated from a factorial combination of three amplitudes, ($A=48$, 84, and 147 mm), four targets widths ($W=3.00$, 5.25, 9.20, and 16.10 mm), and two directions (right and left). The index of difficulty for these targets, $\log_2(2A/W)$, thus ranged from 2.58 bits for the easiest target ($A=48$ mm, $W=16.10$ mm) to 6.61 bits for the hardest target ($A=147$ mm, $W=3.00$ mm).

Subjects alternated between blocked and mixed presentations of the target in an ABBA alternation pattern across 12 days of practice; whether the first day was blocked or mixed was counterbalanced across subjects. For the blocked presentation, subjects received blocks of 18 trials with the same target amplitude and width. The first two trials were practice, one to the right and one to the left, and the remaining 16 trials randomly varied whether the target appeared to the right or left with the constraint that eight targets appeared in each direction. There were a total of 12 blocks of trials corresponding to the different combinations of target amplitude and width, and the ordering of the 12 blocks was randomly chosen. For the mixed presentation, subjects received 12 practice trials of randomly mixed targets, followed by 96 data trials consisting of a random ordering of targets with the constraint that each of the 24 targets appear four times. The second half of the experimental session had the same format. The total duration of each experimental session, whether blocked or mixed, was approximately .5 hr, and subjects were permitted a 2-min break half-way through the session.

## Results

*Asymptotic performance.* Over Days 9-12 subjects appeared to be approaching asymptotic performance in that the daily mean trial times averaged across subjects varied less than 5% about the overall mean of those four days. Median reaction times, movement times, and total times (the sum of reaction time and movement time) were calculated for each subject's performance on each of the 24 targets for each of these last four days. For both the blocked and mixed presentation modes, medians were averaged over right and left presentations of the same target and over days of replication to generate 12 means for each subject on each of the three time measures. A separate linear regression line was then fit to each subject's reaction times, movement times, and total times as a function of index of difficulty. For reaction times, only 4 of the 16 regression slopes (8 subjects x 2 presentation modes) were significantly different from zero ($p<.05$). However, for both the movement times and total times, all but one (Subject 2, position system, blocked presentation) of the 16 slopes were significant ($p<.05$). Excluding the one nonsignificant condition, individual subjects' correlation coefficients ranged from approximately .75 to .95 for the position system, and .91 to .98 for the velocity system for both movement time and total time.

Given the relatively high correlation coefficients obtained for individual subjects, the slopes and intercepts of the regression lines were used as dependent measures in six separate analyses of variance, one for the slope and one for the intercept of each of the three time measures. The three fixed factors of each analysis of variance were subject group (more experienced or less experienced), type of control system (position or velocity), and presentation mode (mixed or blocked).

The analyses of variance of the reaction times revealed no significant effects ($p<.05$) for either slopes or intercepts. Regression lines fit to the reaction-time data averaged across subjects are summarized in Table 1. Mirroring the individual subject data, none of these four reaction time slopes was significantly different from zero at the .05 level.

**Table 1**
**Average Regression Lines for Days 9-12**

| | Position System | Velocity System |
|---|---|---|
| Blocked Presentation | $RT = 322 - 1\,ID; r=-.13$ | $RT = 308 - 1\,ID; r=-.14$ |
| | $MT = 454 + 78\,ID; r=.86^*$ | $MT = -72 + 189\,ID; r=.99^*$ |
| | $TT = 790 + 76\,ID; r=.86^*$ | $TT = 221 + 192\,ID; r=.99^*$ |
| Mixed Presentation | $RT = 334 - 2\,ID; r=-.42$ | $RT = 312 - 1\,ID; r=-.22$ |
| | $MT = 250 + 113\,ID; r=.95^*$ | $MT = -121 + 200\,ID; r=.98^*$ |
| | $TT = 584 + 112\,ID; r=.95^*$ | $TT = 198 + 198\,ID; r=.98^*$ |

Note: $RT$ = reaction time, $MT$ = movement time, $TT$ = total time, $ID$ = index of difficulty, and * indicates $p<.05$.

The analyses of variance on movement times revealed that the velocity control system had lower intercepts, $F(1,4)=13.10, p<.05$, and higher slopes, $F(1,4)=33.21, p<.01$, than the position control system. Main effects of target uncertainty approached, but did not reach, the .05 level of significance for both the intercepts, $F(1,4)=5.70, p<.10$, and slopes, $F(1,4)=6.30, p<.10$. Reflecting this pattern at an individual level, seven of the eight subjects had lower intercepts and higher slopes when the target was completely uncertain. Regression lines fit to the movement time data averaged across subjects are summarized in Table 1 and pictured in

Figure 2. Each point in Figure 2 is the average ... approximately 128 trials, and similar data are presented for total times.

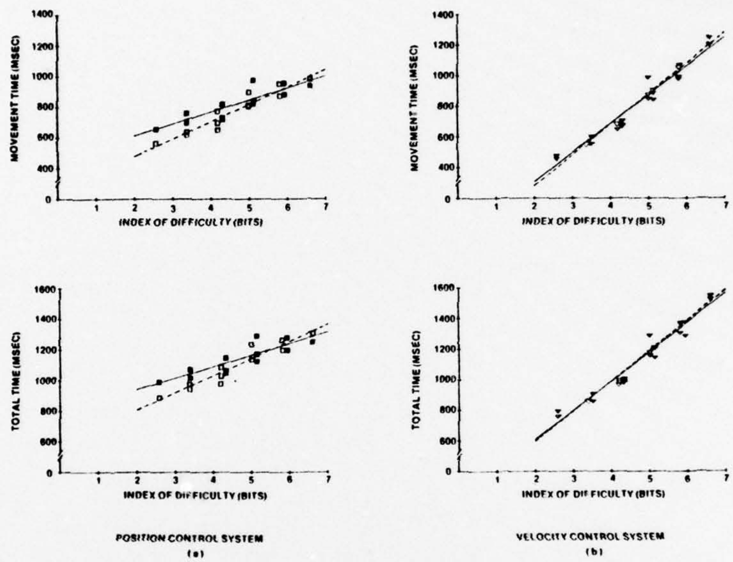


Fig. 2. Means of individual subjects' median times over Days 9-12 and the corresponding regression lines for (*a*) the position control system with blocked (filled squares) and mixed (open squares) presentation modes and (*b*) the velocity control system with blocked (filled triangles) and mixed (open triangles) presentation modes.

The analyses of variance on total times also revealed significantly lower intercepts, $F(1,4)=13.94, p<.05$, and significantly higher slopes, $F(1,4)=37.21, p<.01$, for the velocity control system (see Table 1 and Figure 2). Under conditions of greater target uncertainty, intercepts were also significantly lower, $F(1,4)=8.37, p<.05$, and slopes significantly higher, $F(1,4)=10.26, p<.05$. Finally, the control system x presentation mode interaction approached, but did not reach, the .05 level of significance for both the intercepts, $F(1,4)=5.38, p<.10$, and slopes, $F(1,4)=5.20$, $p<.10$, reflecting a slightly greater effect of presentation mode on performance with the position system.

*Training.* In order to examine the effects of training on subjects' performance, the data for the blocked presentation mode was separated into three time segments corresponding to Days 1-4, 5-8, and 9-12. Regression analyses and subsequent analyses of variance were performed in a similar manner as for the asymptotic performance data. The data for the mixed presentation mode had to be excluded due to procedural errors in stimulus randomization for the early days of several subjects.

Analyses of variance of the slopes and intercepts of the reaction times revealed no significant effects. However, an analysis of variance of mean reaction times did show a significant decrease from 380 msec on Days 1-4 to 312 msec on Days 9-12, $F(2,8)=7.80$, $p<.05$. The intercepts of the movement-time and total-time regression lines did not show any significant change with practice; however, the slopes of both measures decreased considerably. Movement-time slopes changed from 128 msec/bit on Days 1-4 to 78 msec/bit on Days 9-12 for the position control system, and from 291 msec/bit to 189 msec/bit for the velocity control system, $F(2,8)=11.93$, $p<.01$. The total-time slopes were nearly the same values.

Overall, these effects resulted in the mean total time decreasing from 1,362 msec on Days 1-4 to 1,120 msec on Days 9-12, $F(2,8)=13.96, p<.01$. Reflecting the crossover of the position and velocity system regression lines, there was no significant difference in mean total times between the two systems. Although the correlation coefficients for the movement-time regression lines did change with practice, the change was not monotonic. The average correlation coefficients for individual subjects were .82, .89, and .77 for the position system, and .95, .97, and .96 for the velocity system on Days 1-4, 5-8, and 9-12, respectively.

## Discussion

*Effects of system dynamics.* The present results indicate that Fitts' law does generalize to discrete movements executed with a velocity control system. Both movement time and total time were strong linear functions of index of difficulty, whereas reaction time was not significantly affected by this variable. Furthermore, the magnitude of effect of system dynamics was considerable; the movement time versus index of difficulty slope was approximately twice as large for the velocity system. This magnitude of effect is comparable to the differences in slope noted by Langolf, Chaffin, and Foulke (1976) for finger (26.0 msec/bit), wrist (43.0 msec/bit), and arm (105.8 msec/bit) movements. Langolf (Note 3) has noted that the larger slopes are associated with muscles having smaller innervation ratios, as well as involving a larger number of skeletal joints or degrees of freedom that the subject has to control. These two factors were confounded in the Langolf experiments. In the present experiment, both systems required manipulations of the control stick with roughly the same set of muscles; however, the velocity system involved one additional degree of freedom. In other words, control stick position and cursor position always corresponded one-to-one for the position system, but not for the velocity system for which the position output of the system and the position of the control stick could be separately specified. One interpretation of the present data is that increased degrees of freedom result in an increased movement time slope. Whether this generalization may similarly be extended to still higher degree-of-freedom systems remains to be tested.

A second striking aspect of the data is that the superiority of one control system over another depended on the relative accuracy of the required movement. For easy targets with low relative accuracy the velocity system was superior, while the position control system was superior for the more difficult movements requiring high relative accuracy. The crossover point occurred at an index of difficulty of roughly 4.7 bits. These results do not agree with a study by Gibbs (1963) who found the position control system superior by approximately 700 msec vs. 1000 msec for a movement having an index of difficulty of 3.91 bits. In Gibbs' study there was no directional, amplitude, or width uncertainty; however, perhaps a more important difference was that his criterion for completion of the movement was simply that the cursor remain within the target region for 2 sec, and there was no additional steadiness criterion. In order to estimate how strongly the findings in the present study depended on the steadiness criterion, subjects' data for Days 9-12 with the mixed presentation mode was reanalyzed using as a criterion that the cursor simply remain within the target region for 350 msec. Such an analysis probably overestimates total times in that subjects might alter the structure of their movements given a different criterion. Nevertheless, this post-hoc analysis may at least suggest relative sensitivity to criterion variations. Total times ($TT$) for the velocity system were changed less than 35 msec ($TT=141+208\,ID$), while position system total times became shorter by as much as 312 msec for the lowest index of difficulty movement ($TT=169+152\,ID$), and the position system was superior at all the tested values of index of difficulty. This result is not surprising in that one would expect any unsteadiness in the movement of the control stick to be strongly reduced by the low-pass filter characteristics of the velocity system, but not by the position system. At an index of difficulty of 3.91 bits, the new total times were 763 msec and 954 msec for the position and velocity systems, respectively, which agrees reasonably well with Gibbs' values. These results suggest that the stopping criterion may be an extremely critical factor in evaluating the effectiveness of a control system for executing discrete movements. The differential sensitivity to unsteadiness may also explain why the movement time versus index of difficulty regression lines had lower correlation coefficients for the position control system.

*Effects of target uncertainty.* The failure to find any significant effect of target uncertainty on reaction time is surprising. One possible explanation is that subjects did not initially process the additional uncertainty in the mixed presentation mode, and simply executed a stereotyped initial submovement. However, visual inspection of movement trajectories in the phase plane show clear differences in the response to different targets even at the very onset of a movement. Hence this explanation can be rejected. A second possible explanation is the relatively high degree of stimulus-response compatibility in initially displacing the control stick towards the target and also the very extended practice the present subjects had in similar tracking tasks. For example, Fitts (1964) found only a 17 msec/bit increase in reaction time for pointing at one of three lights versus pointing at one of nine lights. The extended practice of the present subjects might have reduced such an effect even further.

The effect of uncertainty on total time can probably be ascribed primarily to processes occurring during the movement time in that the analyses of variance of movement times very nearly exhibited the same pattern of results. While this effect was considerably smaller than the effect of system dynamics, it may nevertheless be of theoretical importance. Given that reaction time does not depend on index of difficulty, the slope of total time versus index of difficulty reflects the relative rate of convergence of the subjects' movement systems toward increasingly more accurate targets. If one assumes that the target is fully identified during the reaction-time interval, then closed-loop explanations of Fitts' law that postulate fixed-parameter movement systems (e.g., Crossman & Goodeve, Note 2; Keele, 1968) have no mechanisms to vary the rate of convergence, and hence cannot predict the change in slope with target uncertainty. Langolf et al. (1976) rejected fixed-parameter linear models of Fitts' law on the basis of average phase-plane trajectories that did not linearly scale with movement amplitude. The results of the present experiment reject linear or non-linear fixed-parameter models of movement.

In rejecting such models, the data suggest that when target amplitude and width are known beforehand, subjects can adaptively alter or "tune" the dynamic response of their movement system as discussed by various investigators (e.g., Fel'dman, 1966; Turvey, 1976). Under conditions of target uncertainty subjects may not be able to tune their response, and the total-time and movement-time slopes would increase either because successive discrete submovements each take longer, or in the case of a more continuous approach to the target, because the rate of convergence was not optimized. A test of this hypothesis will require detailed dynamic analysis of the movement trajectories, which is beyond the scope of the present paper. It should be noted, however, that the present argument assumes that the adaptive alteration of the dynamic response is too slow to be accomplished during the reaction time interval, or else one would not detect an inability to make such adaption under conditions of target uncertainty. This hypothesis also suggests that small effects of uncertainty on movement time as found by some other investigators (e.g., Ells, 1973; Fitts & Peterson, 1964; Fitts & Radford, 1966) may warrant more theoretical interpretation than they have been given in the past.

## Reference Notes


1. McGovern, D.E. *Factors affecting control allocation for augmented remote manipulators.* Unpublished Ph.D. dissertation, Stanford University, 1975.
2. Crossman, E.R.F.W., & Goodeve, P.J. *Feedback control of hand-movement and Fitts' Law,* Experimental Psychology Society Meeting, 1963.
3. Langolf, G.D. *Human motor performance in precise microscopic work.* Unpublished Ph.D. dissertation, The University of Michigan, 1973. (Published by the MTM Association, Fairlawn, N.J., 1973.)

## References

Ells, J.G. Analysis of temporal and attentional aspects of movement control. *Journal of Experimental Psychology*, 1973, *99*, 10-21.

Fel'dman, A.G. Functional tuning of the nervous system during control of movement or maintenance of a steady posture — III. Mechanographic analysis of the execution by man of the simplest motor tasks. *Biofizika*, 1966, *11*, 667-675.

Ferrell, W.R. Remote manipulation with transmission delay. *IEEE Transactions on Human Factors in Electronics*, 1965, *HFE-6*, 24-32.

Fitts, P.M. Perceptual-motor skill learning. In A.W. Melton (Ed.), *Categories of human learning*. New York: Academic, 1964.

Fitts, P.M., & Peterson, J.R. Information capacity of discrete motor responses. *Journal of Experimental Psychology*, 1964, *67*, 103-112.

Fitts, P.M., & Radford, B.K. Information capacity of discrete motor responses under different cognitive sets. *Journal of Experimental Psychology*, 1966, *71*, 475-487.

Gibbs, C.B. Controller design: Interactions of controlling limbs, time-lags and gains in position and velocity systems. *Ergonomics*, 1963, *5*, 385-402.

Keele, S.W. Movement control in skilled motor performance. *Psychological Bulletin*, 1968, *70*, 387-403.

Langolf, G.D., Chaffin, D.B., & Foulke, J.A. An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 1976, *8*, 113-128.

McRuer, D.T., Hofmann, L.G., Jex, H.R., Moore, G.P., Phatak, A.V., Weir, D.H., & Wolkovitch, J. *New approaches to human-pilot/vehicle dynamic analysis*. Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, February, 1968, AFFDL-TR-67-150.

Sheridan, T.B., & Ferrell, W.R. Remote manipulative control with transmission delay. *IEEE Transactions on Human Factors in Electronics*, 1963, *HFE-4*, 25-29.

Turvey, M.T. Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing*. Hillsdale, New Jersey: Erlbaum, 1977.

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Two basic research projects were pursued. In conjunction with personnel at the 6570th Aerospace Medical Research Laboratory, Human Operator Effectiveness Branch, experiments determined that the time to acquire stationary targets with position and velocity control systems was a linear function of an Index of Difficulty measure. This measure, $\log_2\left(\frac{2A}{W}\right)$, is a logarithmic function of initial target displacement, A, and target width, W. The linear relationship with capture time represents an extension of Fitts' Law, known to hold for




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Block 20 (cont.)

discrete movements performed with a physical stylus. The slope of the linear relationship between capture time and the Index of Difficulty was considerably steeper for the velocity control system and was slightly steeper for greater initial target uncertainty.

The second project investigated the capture of moving targets with three different control systems: 1) two independent position controls, PP; 2) two independent velocity controls, VV; 3) one position and one velocity control, PV. The PV system yielded significantly faster capture times than the PP system. However, due to the development of two different control strategies with the VV system the difference between the VV and the other systems was not statistically significant. Further research is recommended to clarify this latter result.

# Process Model of How the Human Operator Tracks Discontinuous Inputs

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